Mars Network Operations Concept

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Abstract - NASA has initiated at Jet Propulsion Laboratory the design of a Communications and Navigation Network at Mars. It will consist of a constellation of low-altitude orbiting satellites and one or more areostationary (of synchronous orbit around Mars) satellites, as sown in Figure 1. The key Mars Network operations concept is to provide standard services and pave a way for interoperability of future Mars Missions. It is envisioned that the Mars Network will provide four types of services: telemetry and command data relay, position determination, time synchronization, and proximity link telecom performance data service. Both scheduled and demand access paradigms were considered as options for the user to access these services. The adoption of the Consultative Committee for Space Data System (CCSDS) Proximity Link (proximity-1) protocol ensures the interoperability at data link level. The CCSDS File Delivery Protocol (CFDP) ensures the interoperability at the message and file transfer level. One important feature of the Mars Network operation is that the orbiting satellites of the Mars Network are indistinguishable from the user's point of view. A user's data transfer transaction started with one satellite can be continued with another satellite. This "cloud" topology greatly simplifies users operations. We also introduce the concept of file based operation. The file based operation for Mars Network promotes autonomous network operations and provides better data accountability.

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1. INTRODUCTION

The Mars Network is a study task initiated at the Telecommunications and Mission Operations Directorate (TMOD) of JPL. The primary objective of the Mars Network is to provide services to the Mars missions in order to support scientific and exploration needs such as Mars global reconnaissance, surface exploration, sample return missions, robotic outposts, and eventual human explorations. In general, the Mars Network provides communications and navigation services at Mars with

- Increased connectivity,
- Increased data rate,
- Precise navigation.

Figure 2 shows the comparative coverage of the planned Mars assets [6].

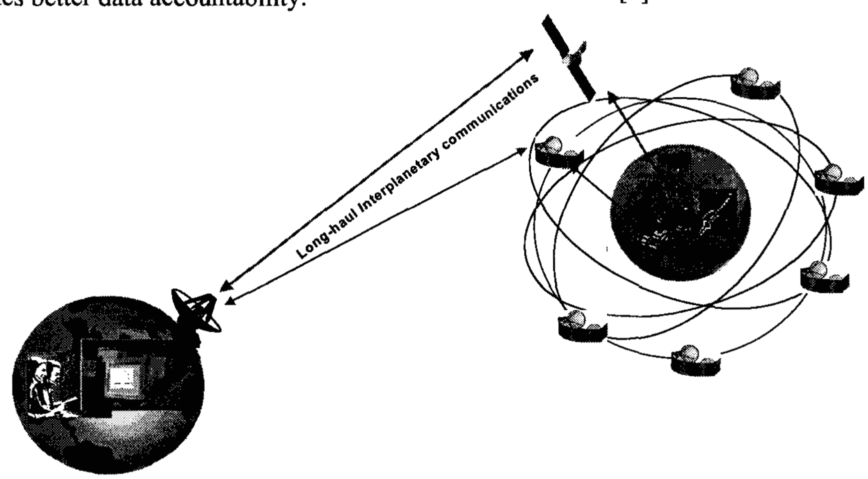

Figure 1 Mars Network

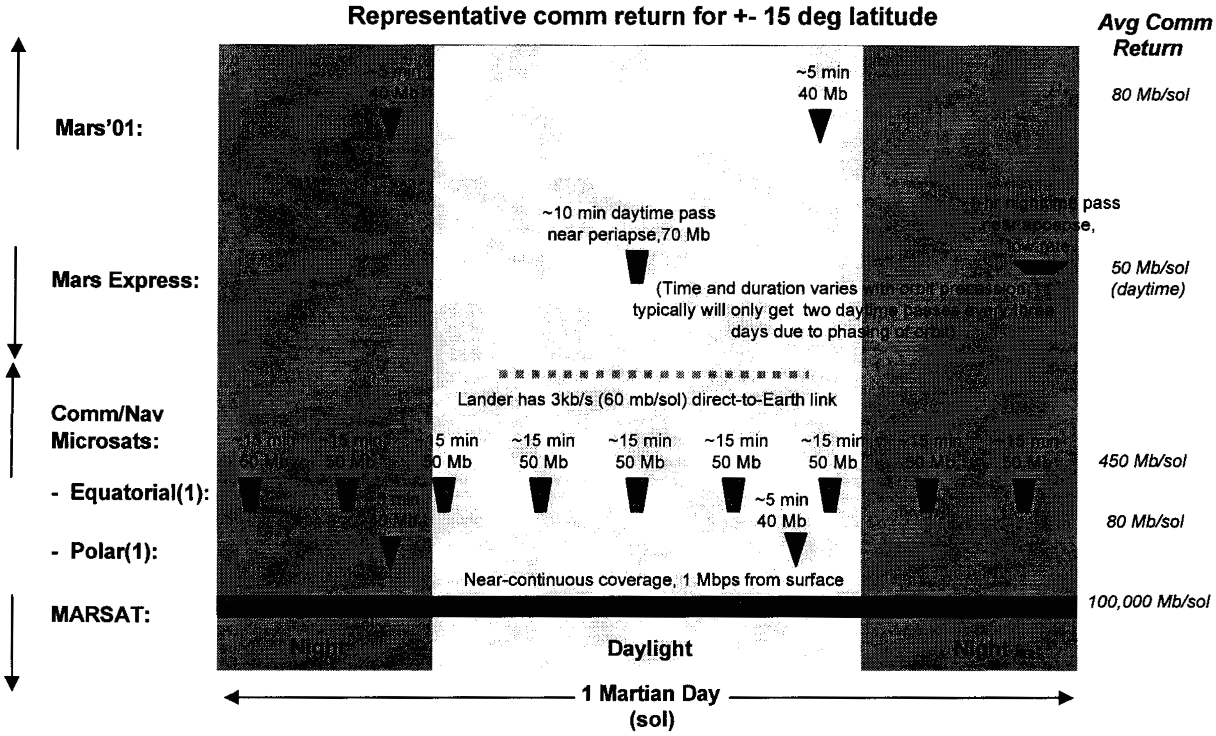

Figure 2 Comparative Coverage of the Planned Mars Assets

The plan is to launch a prototype communications satellite at the end of 2002, which will arrive at Mars in 2003. This first satellite will be in near-equatorial orbit at approximately 800 km altitude to serve the landed elements between +-35 degree latitude. In 2005, two more satellites, one equatorial and one polar, will join the first one to form a constellation. Eventually, it is planned to have 4 to 6 low-altitude orbiting micro-satellites (MicroSat) present. In later years, one or more larger Mars areostationary relay satellites (MARSat) are planned to be at the synchronous orbit to form a complete Mars Network.

With this gradual buildup, the term "Mars Network" refers to the single MicroSat spacecraft of the 2003 era and a constellation of multiple MicroSats of 2005 and after. It extends to include the MARSats in the future years.

Each MicroSat will carry one Ultra High Frequency (UHF) transceiver as the only payload. The traditional NASA mission operations process is well established to deliver the MicroSat to its operational orbit, to maintain its health and safety, to keep track of the operational characteristics and expendables, and to perform payload operations. There is very little station keeping to be performed during a MicroSat's life time. The command and control of the constellation is done by individual MicroSat command and control from the control center on Earth.

The communications between the Mars Network and the Earth is through NASA's Deep Space Network (DSN). A DSN 34-meter subnet that consists of antenna at three different sites globally providing continuous coverage will be dedicated to support the Mars communications need.

2. NETWORK TOPOLOGY, CONNECTIONS, AND END-TO-END DATA FLOW

Network Topology

The Mars Netowrk topology from the user's point of view is shown in Figure 3.

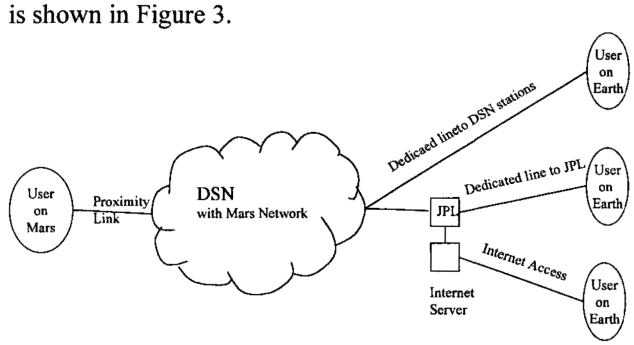

Figure 3 Mars Network Topology

The internal Deep Space Network including Mars Network should be transparent to the user. The user on Mars connects to the Mars Network via the proximity link. The user should not be concerned with which MicroSat it connects to. If a user's telemetry dataset requires multiple proximity link sessions to complete, the sessions can be with different MicrSats. The user telemetry data received at the Mars Network will eventually be forwarded to the DSN stations, merged, and stored at the TMOD server for delivery to the user.

Users on earth, with different arrangements, could access the Mars Network through TMOD in three ways: (1) through special gateway to the DSN stations, (2) through dedicated secure communications line to the JPL inside firewall, (3) through internet access outside the firewall. The differences are in the type of services available and the latency.

Network Connections

Figure 3 shows a connection map. The dashed lines are radio links. The radio links are not permanent links. They are showing here to indicate possible connections. The user elements on Mars that are outside of +-35 degree latitude can not access the equatorial MicroSats. The proximity link and the deep space link to any particular MicroSat does not have to be simultaneous. The merit for MicroSat to MicroSat cross link will be evaluated in the future.

As a store-and-forward communications node, the Mars Network will perform the following functions.

- Link protocols conversion
- Routing
- Flow Control
- Data Priority Handling
- Custody Transfer

End-to-end Data Flow

The Mars Network will support user's end-to-end data system with user selected data format. The prevailing data format in use today for the telemetry data is CCSDS telemetry packet. If user flight element sends telemetry packets to the Mars Network, it will be delivered to the user's control center on Earth in telemetry packets. The user can also interface with the Mars Network in file or other user defined data unit as shown in figure 4.

The earth-bound telemetry, including science and engineering data, are transmitted from the user to the Mars Network over the proximity link. They are multiplexed with telemetry data from other users and transmitted to the Deep Space Network (DSN) ground stations over the Mars-to-Earth space link. The peak data rate of the proximity link using current UHF design is 256Kbps. The data rate for the Mars-Earth space link is a function of the radio frequency, antenna size, and the Earth-Mars geometry (range and angle). For a rough estimate, using the DSN's 34-meter Beam Wave Guide antenna and 80 cm diameter HGA X-band antenna on the MicroSat, the data rate ranges from 5 kbps at 2.5 AU to 150 kbps at 0.6 AU. (It is conceivable that with multiple hops relay satellites properly placed between the Mars and Earth[13], the data rate can be maintained at a constant 0.6 AU range although the propagation delay can not be reduced.)

Protocol Suites

Mars In-situ Communications. Mars Network will support the following protocol suite for the proximity link at Mars.

- Physical Layer: UHF [2]
- Link Layer: CCSDS Proximity-1[2]
- Transport Layer: CCSDS Packet (optional)[4,5]
- Data Delivery Layer: CFDP (optional)[3]

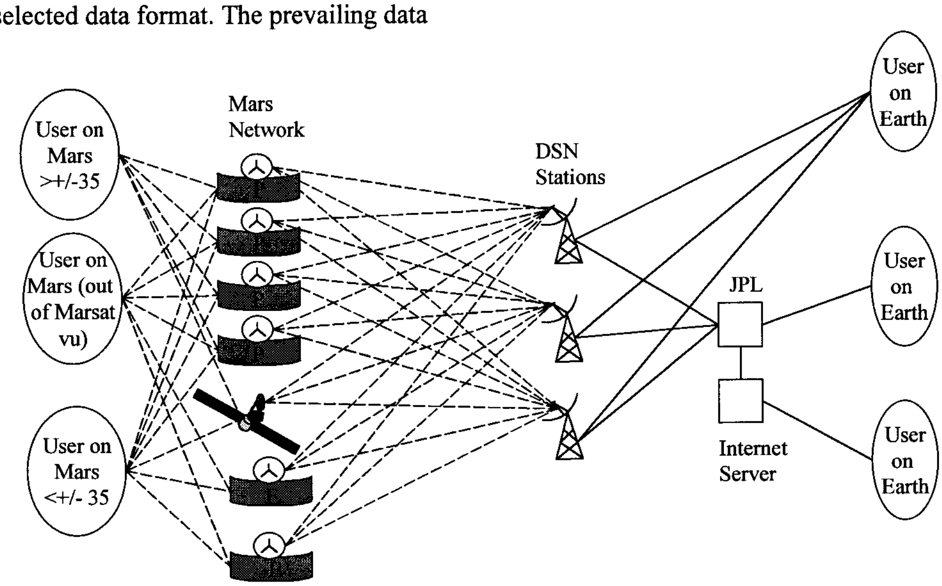

Figure 4 Mars Network Connections

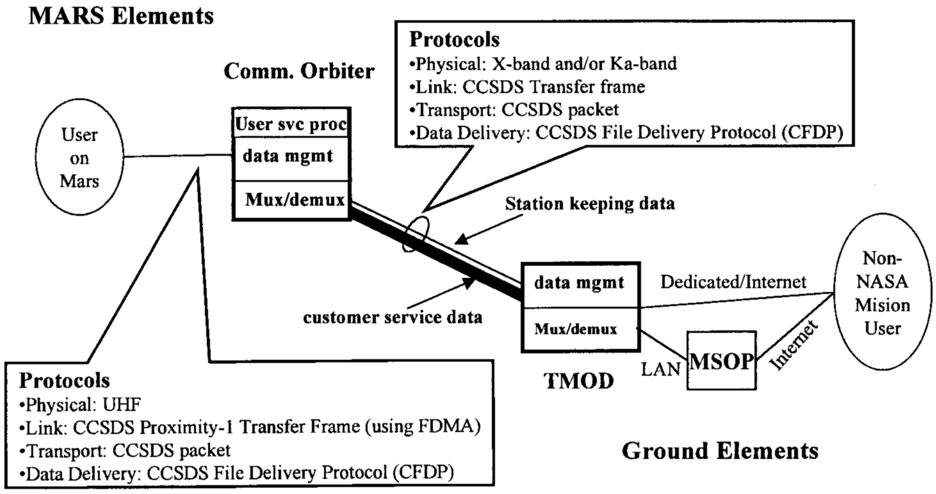

Figure 5 **End-to-end Data Flow**

CCSDS Proximity link protocol defines the Physical and Link Layer standard. The link layer protocol also specifies the link establishment, data transfer, and link termination procedures. It allows any user data to be transferred using the Proximity-1 transfer frame. Therefore, if the user puts the CCSDS packet inside the Proximity-1 transfer frame, the Mars Network will receive the CCSDS packet. If the sender puts the CFDP Protocol Data Unit (PDU) inside the transfer frame, the other end will receive the CFDP PDU.

Mars-Earth Communications. For the long haul communications between the Mars and the Earth, the following CCSDS standard protocol suite will be implemented.

- Physical Layer: X-band and/or Ka-band
- Link Layer: CCSDS Transfer Frame[4,5]
- Transport Layer: CCSDS TM/TC packet[4,5]
- Data Delivery Layer: CFDP[30

3. SERVICE CATEGORY

The TMOD Services Catalog [1] defines standard mission operations services available to customers of TMOD. From the TMOD Service Catalog, customers can make selection for their needed services to support their missions operations without the expenditure of non-recurrent engineering. The Mars Network, as part of TMOD, will provide four types of standard services to the user as described below.

Communications and Data Relay Service[9]

In additional to being a space-born store-and-forward communications node, the Mars Network provides telemetry and command data relay services that extends the current TMOD services to the Mars environment.

Relays user telemetry data from the user element on Mars to the user on Earth. Mars Network provides data priority handling and custody transfer function. Data priority is a parameter of the telemetry data quality of service. The priority within a mission allows the expedite delivery of urgent data over other telemetry data. The priority among multiple missions allows the efficient use of the bandwidth. Custody transfer guarantees the data received by the Mars Network will be eventually delivered to the Earth. Therefore, the user element does not have to hold on to the data once it is acknowledged by the Mars Network.

Relays user command data from the user on the ground (Earth) to the user element on Mars. Mars Network can perform controlled command delivery. The command delivery to the surface element can be specified by time or event. This allows the de-coupling of when the command is needed by the user element and when it needs to be uplinked to the Mars Network.

Relay user data among user elements on Mars. This service can be used when both the source and destination are in view simultaneously or when they are in view at different time. Mars Network will only provide the data routing function similar to UDP.

Navigation Service[10]

Mars Network provides the following navigation services: Surface asset positioning (landers/rovers); Mars orbiting asset state determination (positions and velocities); Positioning for precision landing / atmospheric exploration.

In- Situ Radio Frequency Tracking. The first generation of Mars Network UHF transceiver will perform 1 and 2-way UHF-Band Doppler and Range and 1 and 2-way Open Loop Carrier Recording. The next generation of the

UHF transceiver will be capable of Radio Direction Finding (RDF).

Traditional Earth Based Navigation. Mars Network collects radio frequency tracking observations, package in Network Observables Message (NOM) and send to Earth for user state determination by ground controllers. Solutions are distributed via a standard User State Message (USM).

Network Determined Navigation. User states are determined autonomously by the Mars Network and distributed via a standard User State Message (USM).

User Determined Navigation. User determines own state based on own measurements using the Mars Network as a transponder or with standard Network Observables Messages (NOM) and Network Almanac Messages (NAM).

The format and contents of the NOM, USM, and NAM are being specified and will be proposed to the CCSDS for international standard recommendation.

Timing Service

The current TMOD standard timing service is an after-the-fact time correlation function, which correlate the spacecraft clock time (a clock counter that has an arbitrary epoch chosen by the mission) to the UTC time. This time correlation product is used by the user's control center to process their telemetry data and to generate timed commands. Mars Network extends the timing service to include the time distribution. This is used by the user's flight system to actively update the on-board clock to the Mars Network clock.

Time correlation. This is a three-point process. The user spacecraft clock time is correlated to the Mars Network spacecraft clock time, which in term correlated to the UTC time on Earth.

Time synchronization. In- situ time synchronization via distribution of Mars Network time. A standard format and epoch of the time information needs to be established.

Proximity Link Telecom Performance Data Service

The Mars Network will collect the proximity link performance data and provide them to the user. The link performance data is per link connection basis.

4. SERVICE ACCESS METHODS

User's flight element accesses the Mars Network through the connection of the proximity link at Mars. The CCSDS proximity-1 protocol [2] Medium Access Control (MAC) defines the link establishment, maintenance, and termination procedures. MAC caller uses a hailing frequency (437.1 MHz) to address a responder. The hailing includes the data rate and working frequencies to use. We explore two access methods, scheduled and on-demand, using the MAC procedures. To maintain the compatibility with existing Mars surface elements that did not implement the MAC, it is also possible to access the Mars Network service without using MAC. This is described as a special case of the scheduled access below.

Scheduled Operation

The Mars Network link connection can be scheduled in advance. The user requests the services needed through TMOD. TMOD then schedules the connection based on the view periods and resource availability. The user is notified of the planned link schedule giving sufficient time for the user to send to its flight element if necessary.

In the case where the user's flight element does not understand MAC, it will have to be commanded to establish the link connection with the Mars Network. The start time, link duration, RF frequency, data rate, etc. are uplinked to the flight element by the user. The same information is also up loaded to the scheduled MicroSat. The user's flight element and the MicroSat will turn on the radio at the scheduled time and use the pre-assigned attribute to communicate with each other.

With the MAC, the proximity link is established by the "hailing" method. In this case, the user flight element does not have to have a priori knowledge of the proximity link estabilishment. The link schedule and attribute are up linked to the MicroSat only. The MicroSat hails the user flight element to establish the link. The hailing establishes the working frequency, data rate, and the quality of service. The MicroSat is also responsible for maintaining the communication and terminating the connection. To use this link establishment method, the user's flight element is required to be in low power listening mode to listen for the hailing call.

On-demand Operation

On-demand means the link access is not pre-scheduled. The concept is similar to picking up the telephone handset whenever a telephone call is to be made. For the initial phase, however, the "on-demand" method that can be supported by the Mars Network is the round-robin polling. The MicroSat, as a caller, when comes into view with the surface element, will hail the surface element on hailing frequency. If the MicroSat has data for the hailed element, it will demand a link connection in the call. If the surface element has data to send, the surface element will demand access in the call response. To refuse a link, the surface element can either respond to the MicroSat's call with refusal or let the call timed out.

If more than one surface elements are in view of the MicroSat at the same time, the MicroSat will hail each one in a round-robin fashion.

For the 2003 missions, there will be only a handful of elements on the Mars surface and the on-demand operation can be accomplished without complexity. However, a more sophisticated algorithm is being developed to handle a more complex situation for the future on-demand operations.

5. FILE BASED OPERATIONS

With the advancement of flight computers, operating systems, and mass storage for the flight system, the management of flight data can be vastly simplified if they are treated as files, thus reducing the size of the operations team and its cost. In a similar fashion, sequences and flight software loads can be uplinked and managed as files to ensure reliable delivery and to remove the labor intensive memory management task from the operations team.

The emerging CCSDS File Delivery Protocol (CFDP) [3] will provide reliable file transfer through multiple relay hops with discontinuous sessions, and enables the file-based operations. The file-based operations capture the data and manage them using a file management system. The use of a file management system provides a ready mechanism for tracking file transfer progress and completeness.

What is CFDP and What does it do? CFDP is a file transfer and/or message delivery protocol designed for the space link environment. CFDP provides the capability to move files, manipulate files, and deliver messages.

Moving file is a point-to-point process that transports a file from one file storage to another file storage. The metadata associated with a file is also transported in the move file transaction. The file manipulation process of CFDP performs the load file, replace file, patch file, and append file functions according to the directives contained within the transaction's metadata. Message delivery is an application-to-application function. An application message when included within the metadata, is delivered to the destined application at the time and condition specified in relation to the file transfer. These three elements: moving files, manipulate files, and deliver messages, play important roles in supporting flight operation.

CFDP minimizes handshaking required to start, continue, and complete file transfer. The protocol uses byte offset to identify data location within the file, thus it is insensitive to the data duplication and data transfer order. Each data transfer units has a unique transaction ID which is used to associate the file transfer attributes (source/destination, etc.). The CFDP supports hop to hop custody transfer. It also supports incomplete file delivery and incremental file delivery. Using CFDP, File transfers can span multiple contacts and multiple stations (McroSats/ground stations). It provides efficient operation over simplex, half duplex, and full duplex links.

User Data Management and Delivery

User return data are managed onboard Mars Network as files. The Mars Network creates one or more subdirectory for each user. If the original user data is the CCSDS packets, the packets of one proximity link session are grouped and stored as a file in the sub-directory for that user. If the original data is a file and is transferred to the Mars Network using CFDP, the Mars Network is served as a reliable agent and performs the custody transfer function. It forwards the partial or complete file received to the DSN stations. Multiple partial files forwarded by multiple MicroSats will be merged into one complete file at TMOD ground data system (GDS) before it is delivered to the user.

For a non-NASA user, the file received on the TMOD GDS will be delivered to the user with file server. If a file contains CCSDS source packets, TMOD will provide software tools for the user to retrieve packets from the packet file. For a NASA user, the packet extraction will be done by TMOD and the packets will be stored in the Telemetry Data System (TDS) for retrieval.
User forward data are transferred to the Mars Network using CFDP. The forward data can be a flat file or a Command Packet File. A Command Packet File contains the binary commands for the user's flight element and transport instructions of these commands. Mars Network will deliver the user commands according to the transport instruction. The syntax and semantics of the Command Packet File is a TMOD standard.

User can also use the Mars Network as a reliable agent for the CFDP file transfer. In this case, the file is forwarded as a flat file as soon as a proximity link is established.

Using the on board file management system, the operations team has more flexibility and control of the on board data. The descriptive file name gives the operations team a quick notion of what's in the file. They can selectively retrieve a cluster of files, a particular file, or a partial file. The on board file directory also provides information about the usage of storage area and allows the operations team to update its knowledge about the actual memory state.

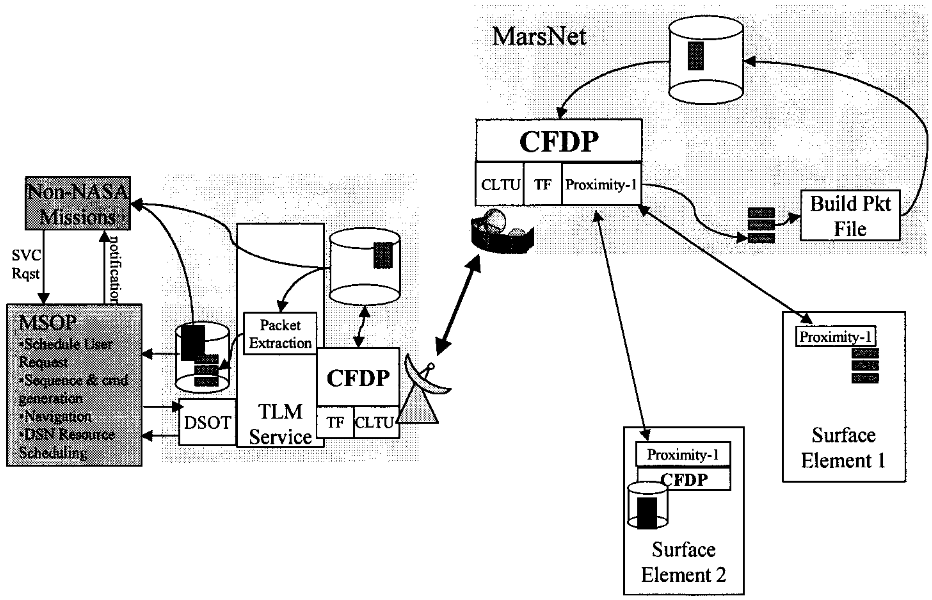

Figure 6 Earth-bound Data Transfer using CFDP

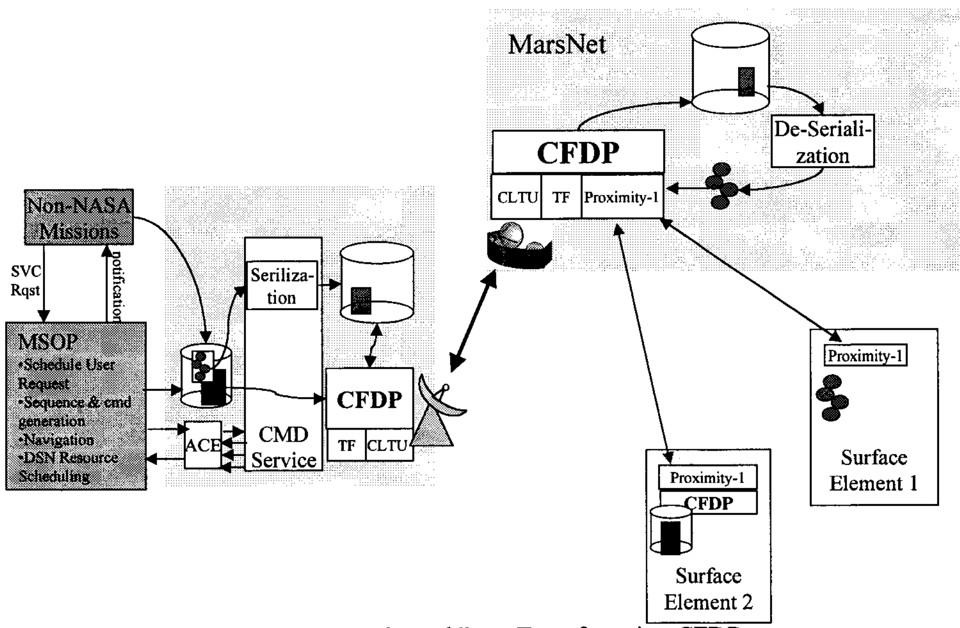

Figure 7 Mars-bound Data Transfer using CFDP

6. CONCLUSIONS

Interoperability and standard access are our main thrust in developing this operations concept. The service operations providing in-situ services to the user on Mars is a new paradigm at NASA. It is a challenge to design a service mission while the user's specific requirements are not completely understood and the usage of the services are not fully planned in advance. We approach this problem by focus in the service definition and service operations

Use of file to capture, manage, and transport data provides easy mechanism for tracking file transfers and their completeness (data accountability). Files provide manageable data units for on-demand as well scheduled data transfers. Custody transfer (hop-by-hop reliability) allows the efficient use of on-board memory. Automatic store-and-forward reduces ground operations involvement. CFDP Protocol enables the file based operation and increases the S/C operability and interoperability.

Mars, as our next frontier in space exploration, will subject to increasing activities in the next Millenium.

Between 2003 and 2010, at least 18 distinct robotic exploration elements are slated for possible deployment at Mars. Many small landers, rovers, penetrators, and robotic probes will roam the Mars surface. These elements have limited power and mass. While some elements will still be built with their own direct-to-Earth communications capability, Mars Network will increase the communications rate, contact time, and contact frequency, thus enhance the mission goals.

Mars Network will also work in concert to provide in situ navigation[7]. Using combined 2-way ranging, three MicroSats will be able to provide position knowledge with an uncertainty about 1 km at 125 km above surface, and within 10 to 100 meters on the surface; compared to using DSN tracking alone, the position knowledge uncertainty is 15 km at 125 km above surface, and 75 km on surface. It is possible to use the Mars Network to assist precision landing and accurate position determination. This navigation capability will enable a whole new level of autonomous robotic, and eventually safe human exploration.

The standard service approach of the Mars Network operations is the first step to make it a gateway to Mars and beyond.

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